Measurement of excitation functions in $^{14}$N- ion induced reactions

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Excitation functions of nine evaporation residues populated through complete and/or incomplete fusion in $^{14}$N + $^{124}$Sn system in the projectile energy range ≈4−7 MeV/nucleon have been measured. Recoil catcher activation technique using offline γ-ray spectrometry has been employed in these measurements. The evaporation residues produced through xn and pxn channels are found to be well reproduced by the theoretical predictions of PACE-4. In case of evaporation residues produced through α-emitting channels, significant enhancement in the measured excitation functions over their theoretical predictions has been observed. This enhancement indicates that these α-emitting channels are attributed to the incomplete fusion process. The comparison of present study with literature data also shows that the ICF probability depends on various entrance channel parameters. A new combined parameter $\frac{Z_eZ_r}{1−\beta_1}\mu_{IC}^\alpha$ has been found to explain more precisely the ICF dynamics than other entrance channel parameters.

Keywords: Excitation functions, Stacked foil activation technique, Complete and incomplete fusion, Incomplete fusion fraction, Projectile structure

1 Introduction

The study of heavy ion induced reactions mainly completes fusion (CF) and incomplete fusion (ICF) has been a subject of resurgent interest to the nuclear physicists. In case of complete fusion (CF) process, entire projectile fuses with the target and the highly excited compound system decays by evaporating low energy nucleons and α-particles at the equilibrium stage. Whereas in case of ICF reactions, only a part of the projectile fuses with the target nucleus, leading to transfer of a fraction of the incident momentum to the target nucleus, while the remainder (generally α-particle) behaves as a spectator and moves in the forward cone. The first experimental evidence of ICF was observed by Britt and Quinton\cite{3}. Major advances in the understanding of ICF dynamics took place after the charged particle-γ coincidence measurements by Inamura et al.\cite{2} for $^{14}$N + $^{159}$Tb system at beam energy about ≈7 MeV/nucleon. Several theoretical models have been proposed to explain the characteristic features of ICF dynamics. Some of the most widely used models to explain ICF data are the Sumrule model\cite{1}, breakup fusion model\cite{2}, promptly emitted particles model\cite{3}, exciton model\cite{4} and overlap model\cite{5}. These theoretical models satisfactorily reproduce the contribution of ICF in some cases at higher energy, i.e., greater than 10 MeV/nucleon. But none of these models can satisfactorily explain the gross features of ICF data at low projectile energy below 7 MeV/nucleon. Hence, a clear picture of the mechanism of ICF dynamics has yet to be established at low bombarding energy. This makes the study of low energy incomplete fusion dynamics still an unsolved area of investigation. The presence of low energy ICF reactions and their dependence on various entrance channel parameters have been studied during the last couple of decades. Morgenstern et al.\cite{6} found that the contribution of ICF to total fusion cross section increases with entrance channel mass asymmetry at relatively higher energies greater than 10 MeV/nucleon. Recently, several investigators have shown great interest to study the dependence of ICF dynamics on various entrance channel parameters\cite{7, 8, 9}. Their studies show that the onset of ICF dynamics does not depend on a single entrance channel parameter, while it depends on various entrance channel parameters.

The present work has been carried out with a motivation to understand the dependence of ICF dynamics on various entrance channel parameters.

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The excitation functions (EFs) of evaporation residues (ERs) populated in $^{14}\text{N} + ^{124}\text{Sn}$ system at projectile energy range $\approx 4-7$ MeV/nucleon have been measured and analyzed within the framework of statistical model code $^{12}$ PACE-4.

2 Experimental Details

The present experiment has been carried out using energetic $^{14}\text{N}^{6+}$ beam delivered by 15 UD Pelletron accelerators at Inter University Accelerator Centre (IUAC), New Delhi. The isotopically enriched $^{124}\text{Sn}$ (abundance = 97.40 %) targets of thickness $\approx 0.1-0.6$ mg/cm$^2$ were prepared by vacuum evaporation method in the target development laboratory of IUAC, New Delhi. The $^{124}\text{Sn}$ targets were deposited on aluminum (Al) - backings of thickness $\approx 1.0-1.5$ mg/cm$^2$. The Al-backings were used as catcher foil and energy degrader to trap the recoiling evaporation residues during the irradiations. The thickness of each target and Al-backing foil has been measured by weighing method using microbalance as well as using $\alpha$-transmission method, which is based on the measurement of energy loss by 5.487 MeV $\alpha$-particles from standard $^{241}\text{Am}$ source. The targets were cut into size of $1.2 \times 1.2$ cm$^2$ and pasted on stainless steel (SS) holders having concentric hole of 1.0 cm diameter. The Al-backings along with deposited $^{124}\text{Sn}$ target material was pasted on SS target holders with silver collider paste for rapid dissipation of heat produced during the irradiations. The recoil catcher activation technique has been employed for the present measurement of excitation functions of evaporation residues produced in $^{14}\text{N} + ^{124}\text{Sn}$ system. The irradiations have been carried out in the General Purpose Scattering Chamber (GPSC) at IUAC, New Delhi. This chamber has an in-vacuum transfer facility (IVTF). The IVTF has been used to minimize the time lapse between the stop of irradiations and start of the counting. A stack consisting of six $^{124}\text{Sn}$ targets along with Al-backings was bombarded with energetic $^{14}\text{N}^{6+}$ beam of energy 85 MeV. The beam current was monitored $\approx 2-4$ pA during the irradiation. The targets along with Al-catcher foils were placed normally to the beam direction so that the recoiling evaporation residues populated during the interaction of projectile with target may be trapped in the catcher foils of suitable thickness. The irradiation was carried out for $\approx 8$ h, keeping in view the half-lives of interest. The beam flux was calculated by the total charge collected in the Faraday cup, placed behind the target- catcher foil assembly, using a current integrator device. After the irradiation, the stack of $^{124}\text{Sn}$ targets along with catcher foils was taken out from the GPSC. The activities produced in each foil was then recorded using a pre- calibrated high resolution high purity Germanium (HPGe) detector of 100 c.c. active volume coupled to PC through CAMAC based CANDLE software $^{13}$. The energy and efficiency calibration of HPGe detector was done using various standard $\gamma$-ray sources of known strength viz. $^{152}\text{Eu}$, $^{60}\text{Co}$ etc. The standard $\gamma$ - ray sources and the irradiated samples were counted in same geometry to keep same geometry dependent detector efficiency in the measurement of excitation functions. The $\gamma$ -ray spectra of individual target-catcher foil assembly were recorded at increasing time intervals. The identification of ERs produced has been done on the basis of their characteristic $\gamma$-ray recorded in the spectrum and also by their decay curve analysis. The characteristic $\gamma$-ray energy, branching ratios and half-lives of ERs have been taken from literature $^{14,15}$. The production cross-section ($\sigma$) for different ERs has been evaluated using the standard formulation given in literature $^{16}$. The errors and uncertainties may arise in the measured cross-sections due to various factors. Main factors are discussed here: the uncertainties in the measured production cross-sections may arise mainly due to (i) the uncertainty due to fluctuations in the beam current during the irradiation (ii) uncertainty due to the non-uniformity of target thickness measurement (iii) error in the efficiency calibration of HPGe detector (iv) dead time losses (v) error due to straggling of ion beam passing through the target. The overall uncertainty from all these factors including statistical errors in the photo peak area is estimated to be less than 15 %.

3 Results and Discussion

In the present work, the cross- sections for the ERs $^{133,136}\text{La}$ (xn), $^{133,136}\text{Ba}$ ($\alpha$xn), $^{134m,132,130}\text{Cs}$ ($\alpha$xn) and $^{131m}\text{Xe}$ ($\alpha$pxn) populated in the $^{14}\text{N} + ^{124}\text{Sn}$ system have been measured. The measured cross-sections of these ERs have been compared with the theoretical predictions of statistical model code PACE-4$^{12}$ to understand the involved reaction mechanism. PACE-4 is a Monte Carlo simulation code based on Hauser-Feshbach formalism used for the determination of the decay sequence of an excited compound nucleus (CN). Bass formulations $^{17}$ are used to calculate the cross-sections for a particular reaction channel.
The angular momentum projections are calculated at each stage of de-excitation of CN, which enables the determination of angular momentum distributions of ERs. The transmission coefficients for the emitted light particles like neutron, proton and α-particle are determined using optical model potentials\textsuperscript{18}. The γ-ray strength functions for the transitions E1, E2, and M1 have been taken from the tables of Endt\textsuperscript{19}, while atomic masses are taken from literature\textsuperscript{20}. The level density parameter ‘a’ (= A /K MeV\textsuperscript{-1}, is one of the most important parameter in this code, where ‘A’ is the mass number of the compound nucleus and ‘K’ is called level density parameter constant, which affects the equilibrium components. Most of the required input parameters have been used as default except the mass and charge of the projectile and target nucleus. In the present study the values of free parameter K has been varied from K = 8, 10 and 12. The sum of measured cross-sections of the ERs \textsuperscript{133-131}La and \textsuperscript{133m}Ba populated via xn/pxn emission channels have been plotted along with PACE-4 predications as a function of projectile energy and displayed in Fig. 1. In these measurements, the measured productions cross-sections for the ER \textsuperscript{132}La of ground as well as meta-stable states have been measured. Thus, the measured total cross-section of the ER \textsuperscript{132}La is the sum of meta-stable and ground state. The ground state of ER \textsuperscript{133m}Ba corresponds to very long half-life and thus, it could not be measured separately. The measured EFs for the production of this ER only correspond to its metastable state. In this case, the total measured cross-sections (metastable state + ground state) would have been expected to be further enhanced after adding ground state contribution as compared to PACE-4 predictions. In Fig. 1, the measured cross-sections of the ERs \textsuperscript{133-131}La and \textsuperscript{133m}Ba are satisfactorily reproduced by the theoretical predictions of PACE-4 code at level density parameter constant K = 10. These results indicate that these evaporation residues are populated through only CF dynamics. The sum of excitation function of ERs produced in the reactions associated with α-particle(s) emission channels \textsuperscript{134m,132,130g,129}Cs and \textsuperscript{131m}Xe are displayed in Fig. 2 along with the theoretical predictions of PACE-4. These ERs are expected to be produced mainly through the incomplete fusion dynamics. It can be clearly observed from this figure that the measured cross-sections are much enhanced over their theoretical values at higher projectile energy. Since ICF is not considered in PACE-4 calculations, this enhancement may be attributed to ICF of \textsuperscript{14}N. It means that these ERs are populated not only by CF of \textsuperscript{14}N but also have a significant contribution from ICF of \textsuperscript{14}N, i.e., fusion of fragment \textsuperscript{10}B with the target \textsuperscript{124}Sn (if \textsuperscript{14}N breaks up into α and \textsuperscript{10}B fragments). The ICF cross-sections for each ER have been deduced as the difference between measured cross-sections and PACE-4 predictions. The ICF cross-sections of all measured ERs have been summed to get the total ICF cross-section of the system at a particular projectile energy. An attempt has been made to estimate the ICF contribution from the measured excitation function data and to study the dependence of ICF dynamics on various entrance channel parameters. The ICF fraction (F\textsubscript{ICF}) has been estimated for the present \textsuperscript{14}N + \textsuperscript{124}Sn

Fig. 1 – Sum of measured cross-sections along with theoretical cross-sections (PACE-4) of evaporation residues populated through xn/pxn channels in \textsuperscript{14}N + \textsuperscript{124}Sn system at energy \approx 4-7 MeV/A.

Fig. 2 – Sum of measured cross-sections along with theoretical cross-sections (PACE-4) of evaporation residues populated through αxn/αpxn channels in \textsuperscript{14}N + \textsuperscript{124}Sn system at energy \approx 4-7 MeV/A.
system. The F_{ICF} is a measure of strength of ICF relative to total fusion (CF and ICF). This incomplete fusion fraction is defined as F_{ICF} (%) = (σ_{ICF}/σ_{CF+ICF}) × 100. The detailed description of determination of ICF fraction is given in our earlier work. The values of F_{ICF} have been taken at a constant value of factor L_R = (ℓ_{max} - ℓ_{crit})/ ℓ_{max} = 0.093, where ℓ_{max} and ℓ_{crit} are the maximum and critical angular momentum of the system, respectively, and their values were calculated using prescription. In earlier studies, Morgenstern et al. systematics show that the ICF contribution is significantly more for more mass-asymmetric system than less mass-asymmetric system. With this view, the measured incomplete fusion F_{ICF} for the present system ^{14}N + ^{124}Sn have been compared with some earlier measurements at a constant value of L_R = 0.093. The F_{ICF} values have been plotted as a function of entrance channel mass asymmetry and shown in Fig. 3. This figure shows that the ICF fraction increases linearly with the entrance channel mass asymmetry of the system, separately for each projectile. This indicates the effect of structure of projectile on ICF dynamics. The dependence of ICF dynamics on various entrance channel parameters has been studied by many authors. Recently, Kumar et al. has suggested that ICF dynamics depends on a parameter \( Z/Z_T \). To understand the role of various entrance channel parameters on ICF dynamics in a more clear way, a new combination of entrance channel parameter has been introduced. This parameter is defined as \( \left( \frac{Z/Z_T}{1 - \beta_2} \right) \). The F_{ICF} values have been plotted as a function of this parameter and shown in Fig. 4. It can be clearly seen from this figure that ICF fraction increases linearly with this parameter. This parameter explains ICF dynamics with more consistency than that of \( Z/Z_T \) and \( \mu_{EC} \). Here, it is also important to mention that the different slopes of F_{ICF} for different projectiles have been observed. This is due to the fact that different projectiles have different values of breakup thresholds. Thus, present results clearly highlight that the structure of projectile simultaneously affect the ICF dynamics along with other entrance channel parameters.

4 Summary and Conclusions

In the present work, EFs of evaporation residues populated via CF and ICF processes in the ^{14}N + ^{124}Sn system have been measured in the energy range ≈4-7 MeV/nucleon. The measured EFs are analyzed within the framework of the statistical model code PACE-4, which includes CF only. The measured EFs of evaporation residues populated through xn/pxn-emitting channels are found to be satisfactorily reproduced by the predictions of PACE-4 code, indicating their production via CF only over the entire energy regime. However, in case of \( \alpha \)-emitting channels significant enhancement in the measured production cross-sections over theoretical predictions has been observed. The observed enhancement may be attributed to the prompt breakup of the non-\( \alpha \)-cluster projectile ^{14}N into \( \alpha + ^{10}B \) leading to ICF dynamics along with literature data.
process. It has been clearly observed that ICF also plays an important role along with CF in case of non α-cluster projectile at these low projectile energies. The dependence of ICF dynamics on various entrance channel parameters for present system along with some other systems taken from literature have also been studied. A new parameter \( \left( \frac{Z_P Z_T}{1 - \beta_2} \right)^{A_S} \) has been taken as a combination of \( Z_P Z_T \), \( \mu_{EC}^{AS} \) and \( \beta_2 \). These results show that the value of \( F_{ICF} \) increases linearly with this parameter, independently for different projectiles. These results also indicate that the structure of projectile simultaneously affects ICF dynamics along with other entrance channel parameters. The present results provide a clear picture on the dependence of ICF dynamics on various entrance channel parameters. The present study suggests that more systematic study regarding the role of various entrance channel parameters on ICF dynamics using non α-cluster structured projectiles is required to get a complete understanding of these reactions at low projectile energy.

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References